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POOL BOILING OF HIGH-FREQUENCY CONDUCTORS

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ABSTRACT

This study presents development of a unique, powerful method for cooling high-frequency, AC conductors that can benefit end users of transformer windings, electrical machine windings, and magnet coils. This method of heat removal involves boiling a dielectric, fluorinert refrigerant that is in direct contact with litz wire conductors. A pool boiling test vessel is constructed, which provides for temperature control of the pool of fluorinert liquid. The test vessel is fitted with viewing ports so that the experiments are observed and studied with the aid of high-speed photography. Tests are performed on a variety of litz wire conductors. The boiling heat transfer coefficient is dependent on the conductor surface roughness. The size of the features on the conductor surface depends on the single-strand wire gage from which the conductor is constructed. All tests are performed with the conductors mounted horizontally. These tests are performed using a DC power supply. The results of these experiments will aid in the design of future cooling systems.

NOMENCLATURE

CHF critical heat flux [W/cm^2]
g gravitational acceleration [m/s^2]
$q_{max,sat}$ CHF at saturation temperature [W/cm^2]
$q_{max,Z}$ CHF predicted by Zuber for infinite flat plate [W/cm^2]
R wire radius [m]

R' non-dimensional wire radius, $R' = R\sqrt{\dfrac{g(\rho_f - \rho_g)}{\sigma}}$

U_v voltage uncertainty [V]
V voltage [V]

Greek Symbols

ρ_f liquid density [kg/m^3]
ρ_g vapor density [kg/m^3]
σ surface tension [N/m]

INTRODUCTION

This study investigates pool boiling as a cooling method for high frequency, AC, litz wire conductors. The power density of high-frequency transformer windings, electrical machine windings, and AC magnet coils could improve significantly through the use of this cooling technology. This increase in performance would permit a decrease in size and weight of power conversion equipment in vehicles, and boost electrical efficiency of stationary power conversion devices. Repetitively pulsed, high-field, research magnets could be made to reach even higher field strengths with greater duty cycles, and consume less power than their present-day counterparts. In addition, this cooling methodology could significantly impact AC "shaker" and "kicker" magnet technology for particle beam accelerators. These magnets could be made more efficient, more compact, and more reliable through the elimination of separately controlled water-cooling systems.

Heat removal from the high-frequency conductors in this study involves the boiling of a dielectric, perfluorinated liquid (Fluorinert, FC-72) that is in direct contact with the conductor. Fluorinerts are non-ozone-depleting, highly wetting, dielectric refrigerants. Fluorinerts have been used for several years as heat transfer fluids in electronic systems including immersion cooling of Cray supercomputers. These fluids are non-toxic, stable, and non-reactive and thus are compatible with most materials. Fluorinerts have been studied extensively and many

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of their properties are well-characterized. Relevant properties of FC-72 are shown in Table 1.

Table 1. Properties of Fluorinert Liquids

Chemical Formula	C_6F_{14}
Boiling Point (°C)	56.6
Dielectric Strength (kV, 2.54-mm gap)	38
Liquid Density (kg/m³)	1599
Liquid Specific Heat (J/kg·°C)	1121
Latent Heat (J/kg)	94280
Liquid Thermal Conductivity W/m·°C)	0.0545
Liquid Viscosity (kg/m·s)	4.47×10^{-4}
Surface Tension (N/m)	8.10×10^{-3}

Pool boiling heat transfer using Fluorinert liquids is being examined in a number of areas. Hong et al. [1] examined the critical heat flux (CHF) of wires at pure-subcooled, gas-saturated, and saturated states of FC-72. They also provided correlations for determining the CHF of cylindrical heaters at these states. Paschkewitz [2] investigated the long-term effects of high voltage electric fields on the physical and electrical properties of FC-72. He found no significant change in the properties of the FC-72 due to these electric fields.

Litz wires are examined in this effort because of their increased efficiency over solid conductors. At high frequencies, the AC current carried by a solid conductor is not uniformly distributed over its cross-section. In the case of a solid, round wire, the current density reaches its maximum at the wire's surface and a minimum at the center. This non-uniform distribution of current is known as the "skin effect." Eddy currents within the conductor cause the AC current to flow at the conductor's surface, therefore, the inner cross section of the wire is essentially unused. A large-cross-section conductor enables these eddy currents to circulate over significant surface areas resulting in wasted power and undesirable heating.

Litz wires carry higher current densities at lower AC resistances compared with solid conductors. These wires consist of a bundle of fine, separately insulated strands of wire. The term litz wire is derived from the German word Litzendraht meaning folded or turned-up stranded wire. Generally defined, it is a conductor constructed of individual, film-insulated wires braided together such that each strand tends to take all possible positions in the cross section of the conductor.

This multi-strand configuration of the litz wire minimizes the power losses resulting from the skin effect and eddy currents otherwise encountered in a solid conductor. Subdividing the conductor into individual, isolated strands and transposing them appropriately equalizes the flux linkages and reactances. This equalization produces more uniform current distribution in the conductor without significantly reducing the current carrying capability. Uniform current distribution and minimization of eddy currents results in a significant increase in conductor efficiency. Also, the braided nature of the litz wire cable provides grooves and cavities resulting in an increased number of nucleation sites creating an enhanced boiling surface.

The majority of pool boiling studies with cylindrical heaters have been performed using solid conductors. Heat transfer from solid conductors is often enhanced using techniques such as foamed channels, roughened surfaces, and surface vibration (Webb [3]). O'Connor and You [4] investigated a painting technique to generate surface microstructures (artificial cavities) to enhance the boiling surface. These artificial cavities are well known to promote enhanced nucleate pool boiling, but very little investigation has been done in the area of pool boiling enhancement of twisted cable bundles. The experiments that have been performed on cable bundles are often not twisted so they do not benefit from the large number of nucleation sites generated by the cavities created by the overlapping wires.

The goal of this study, therefore, is to examine the pool boiling heat transfer characteristics of litz wires immersed in saturated FC-72. Tests are performed on a variety of litz wire conductors mounted horizontally. The boiling heat transfer coefficient is dependent on the conductor surface roughness. The roughness of the conductor surface depends on the single-strand wire gage from which the conductor is constructed. These tests are performed using a DC power supply.

EXPERIMENTAL APPARATUS AND PROCEDURE

A test facility was designed and constructed to maintain a pool of FC-72 at its saturation temperature, while allowing the observation of pool boiling from the litz wire conductors. A schematic of the test facility is shown in Fig. 1.
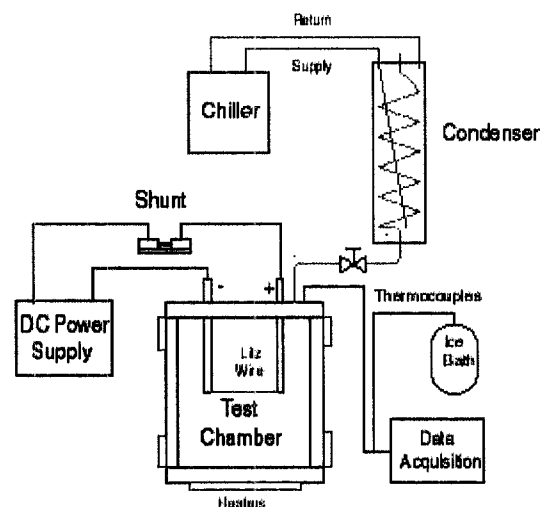

Fig. 1. Schematic of Experimental Apparatus.

The experimental apparatus used for this investigation consists of a boiling chamber and an external condenser. An aluminum vessel (9 in. high, 10 in. OD and 9 in) ID, is used for the boiling chamber. Three flexible heaters are secured to the test chamber, two 2 in. x 20 in. (400 W) heaters on the sides and a 4 in. x 8 in. (320 W) heater on the bottom. These are used to de-gas the FC-72 and maintain the saturation temperature during testing. Insulation covers most of the test chamber. Two, 5-inch Lexan windows are on the sides of the test chamber so that the boiling phenomena can be observed and photographed with a high-speed digital camera.

The lid of the boiling chamber is made of ½-inch aluminum plate. Attached to the lid of the vessel are two, ¾-inch, high-current, insulated power feedthroughs that conduct the input power and affix the high-frequency conductors. Thermocouple ports, a pressure relief valve, and an electric barometer are also attached to lid of the test vessel. Also attached to the boiling chamber is a condenser that is open to the atmosphere at the top. This allows dissolved gases to escape while condensing the working fluid. A chiller maintains the shell side temperature of the condenser at 17°C.

An 8-V, 1000-A, DC power supply is used to heat the litz wire test specimens. This power supply is connected to a PC and controlled using data acquisition software. An HP 34970A data acquisition system connected to a PC running LabView was used to collect data. Temperature measurements were made using ten, type-T thermocouples. Two thermocouples measure the bulk liquid temperature, one measures chamber vapor temperature, one is attached to each of the power feedthroughs, and the other five thermocouples are attached to the litz wire test specimen. Each thermocouple has an external reference junction placed in an ice bath. An Empro shunt is used to measure the current delivered to the litz wire. The resistance of the shunt is 0.00005 Ω with an accuracy of ±0.25%.

Litz Wires Tested

Five different litz wire configurations were investigated and are shown in Table 2. All wire samples were obtained from the New England Electric Wire Company (NEEWC). Of these configurations, two types of round wires and one type of rectangular wire were examined, as shown in Fig. 2. The first type, Type 1, was a single bundle of polyurethane/nylon coated strands of wire in three sizes. The construction information refers to the number and gage of the wires that comprise the bundle. For example, a Type 1 wire bundle with a 17/28 construction is composed of 17, 28-gage wire strands. The second type, Type 2, is bundle made up of three Type-1 bundles, each of which is composed of 35, 36-gage wire strands. The rectangular litz wire (Type 8) is constructed of 8 bundles of wire, each with 7 strands of 33 gage wire, which are then compressed into a rectangular shape.

Table 2. Litz Wire Specimens

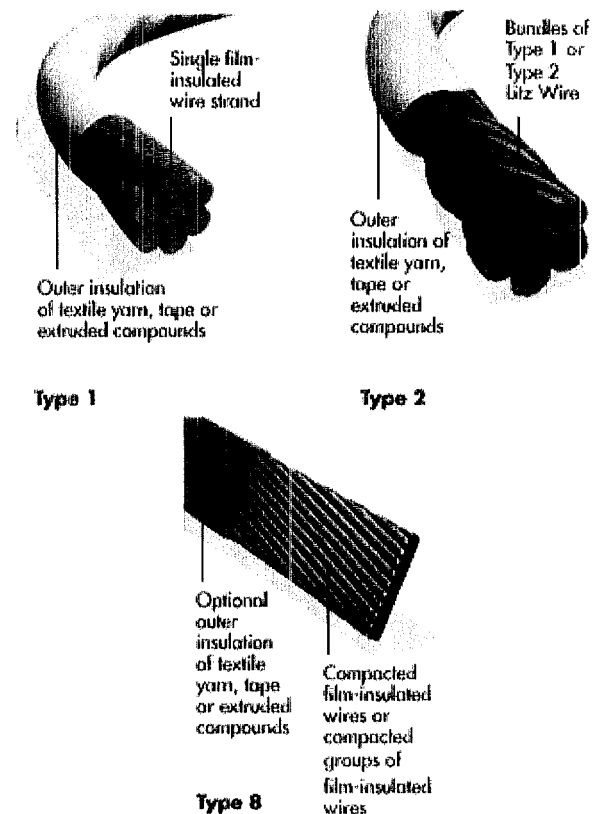| Type	Construction	Nominal Diameter (in)	Width (in)	Thickness (in)
1	17/28	0.065	n/a	n/a
1	26/30	0.064	n/a	n/a
1	53/33	0.066	n/a	n/a
2	3x35/36	0.073	n/a	n/a
8	8x7x33	n/a	0.094	0.045

**Fig. 1. Examples of Litz Wire Cable Bundles Manufactured by New England Electric Wire Company.**

The shapes and cross sectional views of the litz wires examined are shown in Fig. 3. All the litz wire bundles tested had an equivalent, nominal wire gage of 16, when compared to that of a standard wire. For the purpose of calculating surface area for the multi-stranded litz wires, each configuration was assumed to have a circular diameter equal to that of its nominal diameter. For the rectangular litz wire, the surface area was computed using its perimeter based on width and thickness. A 16-gage, solid copper wire was also tested so that it could be compared with the litz wire results.
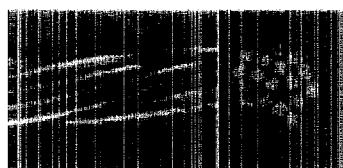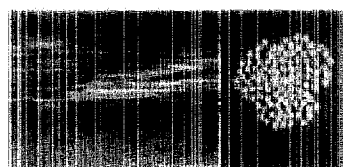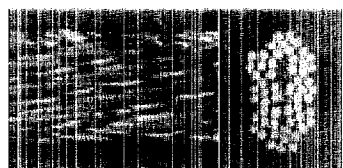
Type 1 (17x28)
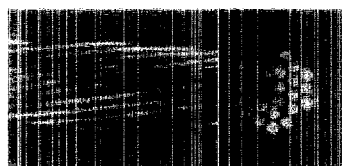
Type 1 (26x30)
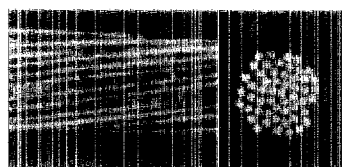
Type 1 (53x33)

Type 2 (3x35x36)

Type 8 (8x7x33)

Fig. 3. Photographs of Litz Wire Specimens (all photos have same length scale).

The length of the litz wires tested was set at 6 in. This length was based on heat loss calculations to the ¾-inch copper power feedthroughs. Using a 1-D analysis, conduction losses to the copper feedthroughs were estimated to impact up to 0.75 in. from the ends of the litz wire test specimen. In order to minimize the effect of the feedthroughs on the heat transfer data, therefore, thermocouples attached to the litz wires were placed in the wire at a distance equal to or greater than 1 inch from the feedthrough.

Preparation of Test Specimens

Litz wire specimens were prepared by cutting pieces of wire 7.5 in. long and placing the ends into a 60/40-tin/lead solder pot at 375°F. The melted solder removes the polyurethane/nylon insulation from the individual strands of wire. Copper washers were then soldered onto the ends of the litz wire. 20-gage copper leads were soldered to each copper washer to measure the voltage across the litz wire. Five, type-T, 40-gage thermocouples were mounted to the specimen, spaced 1-inch apart starting from the center of the wire. Five thermocouples were used to reduce the amount of thermal interference while maintaining the ability to detect CHF before burn out. Tests performed with fewer thermocouples often reached burn out before CHF was detected.

The thermocouples were attached to the specimen using Omegabond 101 epoxy loaded with copper powder to increase the epoxy's thermal conductivity. The mixture ratio of epoxy to copper powder was 2 to 1. Each thermocouple was attached in the center of the wire bundle with epoxy covering the thermocouple junction. Figure 4 shows thermocouples attached to a typical litz wire specimen that is mounted between the power feedthroughs.
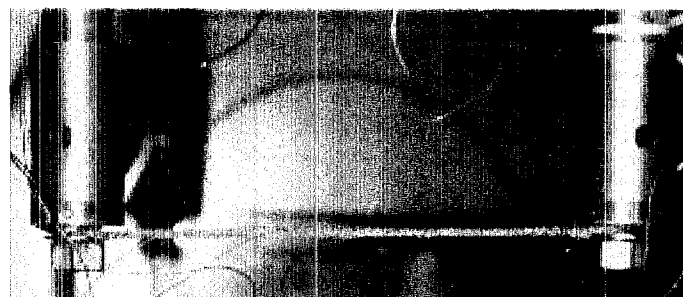

Fig. 4. Litz Wire Specimen Connected to Power Feedthroughs.

Test Procedure

Power is supplied to the electric heaters attached to the boiling chamber to initiate boiling on the sides of the chamber. The test liquid is allowed to boil vigorously for approximately two hours to remove dissolved gasses. After degassing, the power to the chamber heaters is reduced so that boiling on the chamber walls ceases, however, the bulk liquid is maintained at saturation conditions, typically 51.4 °C at 11.8 psia.

The data acquisition software controls the power input to the litz wire and the collection of heat transfer data. The software is programmed to increase the heat flux by controlling the supply voltage in the litz wire. Voltage is increased by 0.1 VDC at the beginning of the boiling curve (near incipience) and when the conductor approaches CHF. Throughout the rest of the boiling curve, the voltage increased by 0.3 VDC. The voltage is incremented to the next power level after the wire has reached steady state. Steady state is determined by calculating the averages of 120 consecutive data points for each thermocouple on the conductor, and comparing them to the averages of a

second set of 120 data points. When the amount of temperature change in each of the five thermocouples is less then 0.2°C from one average to the next, steady state is assumed. After the wire reaches steady state the voltage, current, and temperatures are recorded and the voltage is increased. The determination of CHF is made by monitoring the litz wire temperature for a sudden increase of greater than 15°C. The heat flux value at CHF was obtained by adding half of the heat flux increment to the previous steady state heat flux.

Five different litz wires and one solid copper wire were tested. Two specimens of each configuration were placed in the test chamber. Each litz wire cable was tested three times to ensure repeatability in the data and to confirm that the wire had not been damaged by burnout. All tests are performed with the conductors mounted horizontally. The rectangular Litz wire was tested in two horizontal orientations: with the wide side upward (horizontal), and with the narrow side upward (vertical).

Uncertainty Analysis

The method of Kline and McClintock [5] was used to determine the uncertainty in the experimental apparatus. The uncertainty of the measured voltage was determined by using the HP 34970A specifications for a maximum of 1 VDC:

$$U_v = \pm (0.00015V + 50 \text{ mV}) + 0.00005V \qquad (1)$$

where V is the voltage level. The 1000-A, 50-mV Empro shunt has an uncertainty of ±0.25%. Using these two values the accuracy of the calculations for the current was determined to be 2.77 A. These values were then used to determine the accuracy of the heat flux calculations. The heat flux uncertainties for each litz wire tested are shown in Table 3. These uncertainties were calculated for a voltage of 1 VDC and a current of 500 A.

**Table 3. Uncertainty Values for Litz Wire**

Type	Construction	Uncertainty ($\pm$W/cm^2)
1	17/28	0.352
1	26/30	0.356
1	53/33	0.346
2	3x35/36	0.314
8	8x7x33	0.258

In order to improve their accuracy, each thermocouple was calibrated using a precision RTD and a constant temperature bath. The thermocouples were placed in the bath and measurements were recorded. Temperature measurements were taken from 50 to 100°C because this was the normal range of temperatures for the experiment. This measured data set was used to create a linear curve fit for each thermocouple. An accuracy of ±0.1°C was calculated for the thermocouples with a resolution of 0.025°C for the RTD and a maximum error introduced by the curve fit of ±0.073°C.

RESULTS AND DISCUSSION

During the experiments, high-speed digital images (shown in Fig. 5) were taken of the wires at boiling incipience, nucleate boiling, and film boiling. From these images it was determined that the thermocouples caused the wire to heat differently at their location. This was discovered by the fact that the bubbles leaving the location of thermocouples were larger than those leaving other parts of the wire.
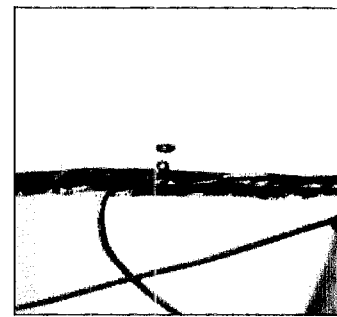
Boiling Incipience

Nucleate Boiling

Film Boiling

Fig. 5. Boiling On Litz Wire Specimen.

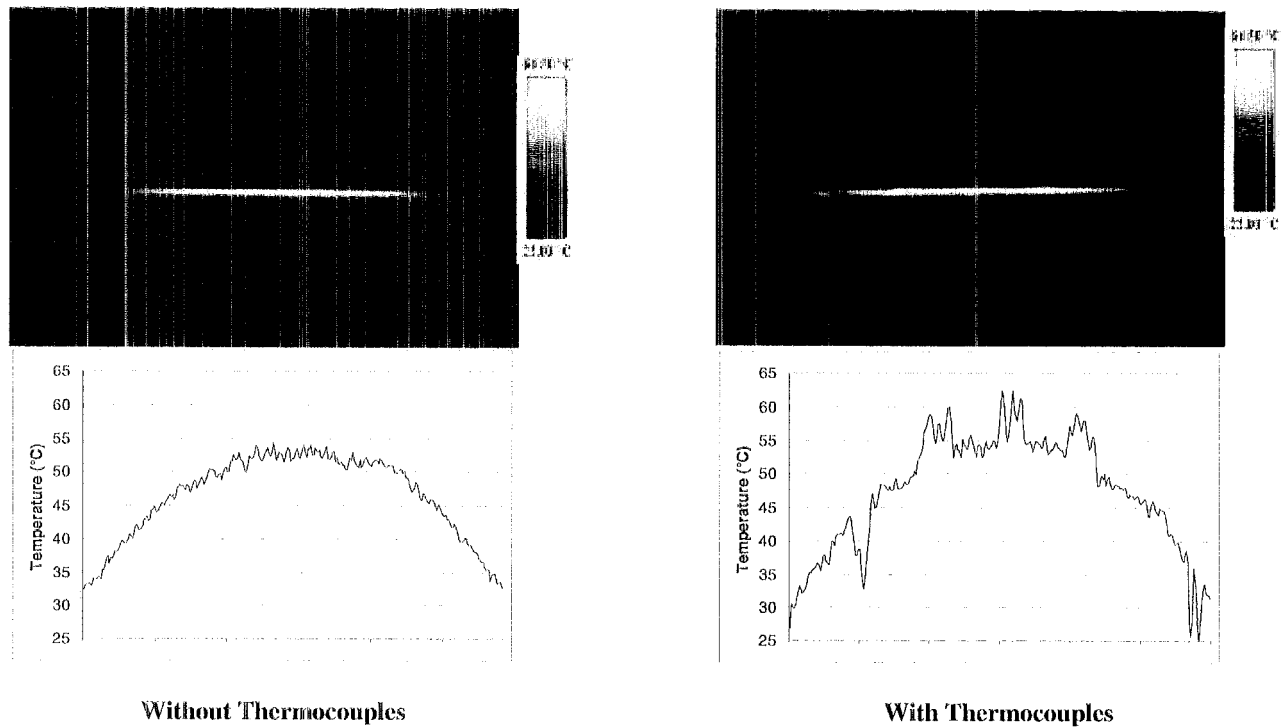Without Thermocouples   With Thermocouples

Fig. 6. IR Images of a Type 8 Litz Wire, With and Without, Thermocouples.
(A wire passing between the litz wire and the IR camera causes the downward spike in the right-hand figure.)

Infrared Imaging

In order to determine the effect of the thermocouples on the heating of the litz wire, infrared images were taken. These images, shown in Fig 6 for the Type 8 litz wire, were taken in air at a wire power of approximately 1.2 W. (The downward spike in the figure with thermocouples is caused by wire passing between the litz wire and the IR camera.) The emissivity of the litz wire was determined to be 0.66. This was found by placing a small piece of Scotch Super 33+ tape on the wire. The tape has a known emissivity of 0.95. The temperature of the tape is assumed to be the same as the wire. A temperature measurement is taken on the tape and the camera is then moved to measure the temperature on the wire right next to the tape. The wire emissivity is then adjusted until the two temperatures are the same.

After taking infrared images of all the litz wires, with and without thermocouples, it was found that the thermocouples caused a local increase in temperature on the wires ranging from 5 to 10 °C. This means that the measured litz wire temperatures are conservative. A possible remedy for this effect would be to use a non-invasive temperature measurement sensor such as an infrared detector.

Heat Transfer Performance

Boiling curves for each of the wires tested are shown in Fig. 7. The heat flux dissipated is shown on the ordinate. The abscissa is the corresponding surface temperature rise of the heating element above the saturation temperature of the liquid. The heater temperature used in this plot is the average of the 5 temperatures measured along the wire.

The solid wire exhibited the second best nucleate boiling heat transfer performance of the 7 configurations tested. Even though it does not benefit from the enhanced surface structure of the litz wires, the solid wire does not have the added thermal resistance of the litz wire insulation. Heat transfer from the wire strands within a litz wire is impeded because each strand is individually insulated. The more wires in a bundle, therefore, the more difficult it is for the heat to be dissipated.

The Type 2 (3x35/36) demonstrated the best heat transfer performance in the nucleate boiling regime. The Type 2 wire is composed of the smallest wire gage, thus providing the most favorable surface structure for boiling enhancement. In addition, even thought the Type 2 litz wire is composed of 105 individual wire strands, it is constructed with 3 separate bundles of 35 wires each. It is possible that this construction reduces the distance from an individual strand in the center of the Type 2 wire to the surface.
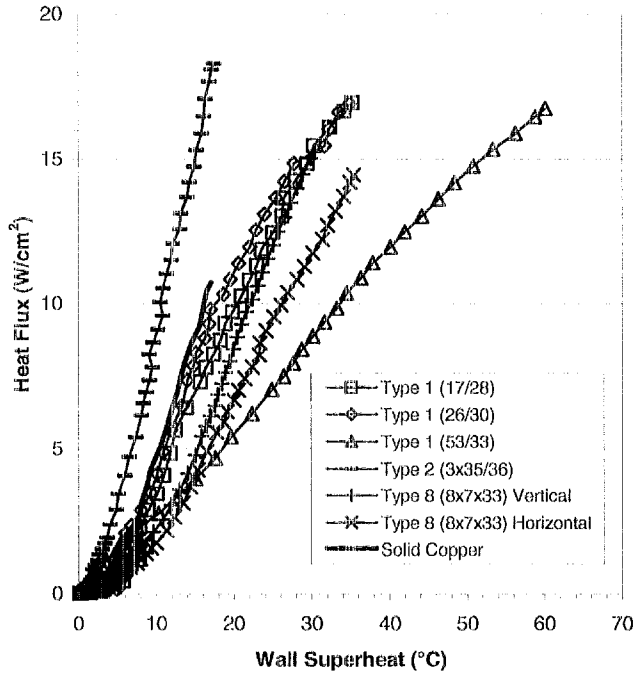
Fig. 7. Boiling Curves for Test Specimens.

The comparison between the two Type 8 configurations shows that the vertical orientation performs better than the horizontal. This is expected since the horizontal orientation results in a larger downward facing flat area where vapor can collect and impede liquid flow back to the surface.

Critical Heat Flux Predictions

Experimental and predicted CHF values for the wires tested are shown in Table 4. Critical heat flux predictions for a solid wire of the same diameter as each specimen were calculated using the correlation of Hong et al. [1].

$$\frac{q_{max,sat}}{q_{max,z}} = 0.89 + 1.01e^{-2.18\sqrt{R'}} \tag{2}$$

where $q_{max,z}$ is CHF predicted by Zuber for infinite flat plate and R' is dimensionless wire radius defined by:

$$R' = R\sqrt{\frac{g(\rho_f - \rho_g)}{\sigma}} \tag{3}$$

Table 4. Critical Heat Flux

Wire	Surface Area (cm²)	CHF Experiment (W/cm²)	CHF Predicted (W/cm²)
Type 1 (17/28)	7.90	17.5	14.5
Type 1 (26/30)	7.78	16.7	14.5
Type 1 (53/33)	8.03	18.4	14.5
Type 2 (3x35/36)	8.88	19.2	14.3
Type 8 (8x7x33) Horizontal	10.76	15.2	13.1
Type 8 (8x7x33) Vertical	10.76	15.4	13.1
Solid Copper	7.78	11.0	14.5

Enhancement in CHF for the litz wires ranges from 1.15 to 1.34 times the predicted CHF for a solid wire of the same size. This enhancement is likely due to the enhanced surface structure caused by the braided nature of the small strands of wire comprising the litz wire. The Type 2 (3x35/36) has the largest enhancement. In addition, the orientation of the rectangular litz wire had little effect on how the wire performed. The rectangular wire's diameter was approximated using the hydraulic diameter.

All litz wire configurations show CHF enhancement over that of the solid copper wire ranging from 38 to 75%. The solid wire's experimental CHF, however, is 24% below its predicted value. This degradation in CHF performance is attributed to the method of thermocouple attachment. The thermocouples are fixed to the wires using epoxy, which causes local hot spots as seen in the IR images. These hot spots can lead to reduced values of CHF. It is possible, therefore, that the experimental litz wire CHF values will increase if a non-invasive temperature measurement technique is used.

CONCLUSIONS

This study presents the pool boiling heat transfer results for litz wires immersed in saturated FC-72. The following conclusions resulted from this study:

(a) The braided nature of the litz wires provides a favorable surface structure for boiling enhancement. This enhancement can be realized as litz wire bundles are configured such that the heat transfer resistance from the center of the bundle to the surface is not too large.

(b) The CHF from the litz wires is significantly enhanced over that of a solid wire. This enhancement is also due to the enhanced surface structure of the braided wire strands.

(c) The use of epoxy to attach thermocouples to the wires caused local hot spots on the wires. These hot spots resulted in a degradation in heat transfer and CHF performance.

ACKNOWLEDGMENTS

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